Applications of Satellite Ocean Color Sensors for Monitoring and Predicting Harmful Algal Blooms

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ABSTRACT

The new satellite ocean color sensors offer a means of detecting and monitoring algal blooms in the ocean and coastal zone. Beginning with SeaWiFS (Sea Wide Field-of-view Sensor) in September 1997, these sensors provide coverage every 1 to 2 days with 1-km pixel view at nadir. Atmospheric correction algorithms designed for the coastal zone combined with regional chlorophyll algorithms can provide good and reproducible estimates of chlorophyll, providing the means of monitoring various algal blooms. Harmful algal blooms (HABs) caused by *Karenia brevis* in the Gulf of Mexico are particularly amenable to remote observation. The Gulf of Mexico has relatively clear water and *K. brevis*, in bloom conditions, tends to produce a major portion of the phytoplankton biomass. A monitoring program has begun in the Gulf of Mexico that integrates field data from state monitoring programs with satellite imagery, providing an improved capability for the monitoring of *K. brevis* blooms.

Key Words: SeaWiFS, chlorophyll, harmful algal bloom, remote sensing, Gulf of of Mexico, Florida.

INTRODUCTION

Harmful algal blooms (HABs) are a recurring problem along US coastlines with the bio- toxins produced by the algae having numerous human, economic and ecosystem impacts (Anderson 1995). In the past few years, considerable attention has been paid to these blooms, in order to determine ways to reduce the impact and health risks. Mitigating HAB impacts requires an ability to monitor for blooms and to forecast their development and movement. Remote sensing can offer a means to aid in this monitoring and forecasting.

HABs are caused by several organisms, each with different characteristics and life histories. These factors influence the potential effectiveness of remote sensing for monitoring. For remote sensing to be effective, the organism must be detectable,

either directly through its effect on the water color, or indirectly by correlation with other algal blooms or association with a water mass that can be monitored by other remotely sensed characteristics such as sea surface temperature (Tester *et al.* 1991; Keafer and Anderson 1993).

Tester and Stumpf (1998) provided a description of various remote sensing capabilities and their usefulness for monitoring of harmful algal blooms (Table 1). Of the several organisms causing HABs, only *K. brevis* has been shown to have the potential to be directly detected by satellite (new studies off the California and Washington coasts will determine the potential of detecting *Pseudo-nitzschia* spp.). Haddad (1982) and Steidinger and Haddad (1981) demonstrated that a major bloom of *K. brevis* could be seen from a satellite ocean color sensor. Tester and Steidinger (1997) have provided the most extensive review on *K. brevis* ecology.

The most direct means of observing *K. brevis* is through chlorophyll concentration. While *K. brevis* has some unique pigments (Millie *et al.* 1997), absorption by these pigments is not sufficient to distinguish it from most other dinoflagellates and diatoms with the six spectral bands found on SeaWiFS. Other approaches drawing on scattering and identification of other blooms are being investigated at present (C. Brown, NOAA, pers. comm.). Laboratory studies indicate that, typically, 100,000 cells l^{-1} corresponds to 1 $\mu g\ l^{-1}$ of chlorophyll (Tester *et al.* 1998; R. Greene *et al.* U.S. Environmental Protection Agency, pers. comm.). Satellite can detect *K. brevis* along the Florida coast at concentrations above 50,000 cells l^{-1} (Tester *et al.* 1998), particularly as background variations in chlorophyll are 0.1 to 0.5 $\mu g\ l^{-1}$.

As closures of shellfish beds occur when *K. brevis* is measured at > 5000 cells l^{-1}, remote sensing is not sufficient to determining shellfish toxicity. But remote detec-

Table 1. HABs and remote sensing.

Location	organism	characteristics	remote sensing detection
northeast	*Alexandrium* spp.	low % biomass	no detection water mass movement (SST) (Keafer and Anderson, 1993)
southeast/ Gulf of Mexico	*Gymnodinium breve*	high % biomass;	ocean color (directly) (Haddad 1982; Steidinger and Haddad, 1981; Carder and Steward, 1985) SST for water mass movement (Tester *et al.* 1991)
west	*Pseudo-nitzschia australia*	correlated to biomass	ocean color (indirectly, possibly directly), SST for upwelling
east	*Pfiesteria* spp.	Low % biomass; episodic	limited

tion is useful for other effects. Concentrations greater than 100,000 cells l^{-1} produce respiratory distress in humans, fish kills, and deleterious effects on marine mammals. Severe blooms can reach concentrations of > 10^6 cells l^{-1}.

All the ocean color sensors have the capability of determining chlorophyll-a and some optical properties of materials in the water (Table 2). SeaWiFS, the current operational ocean color sensor, offers a means of observing *K. brevis* in the eastern Gulf of Mexico. SeaWiFS data can provide a good estimate of chlorophyll, provided the data sets are processed with atmospheric correction algorithms that compensate for scattering by suspended sediments in coastal waters and with regionally appropriate chlorophyll algorithms. The standard global chlorophyll algorithm tends to overestimate chlorophyll in the coastal Gulf of Mexico by a factor of 2 for chlorophyll concentrations > 0.5 µg l^{-1}. Artifacts in the atmospheric correction, when a coastal correction is not applied, may increase this error another twofold. An algorithm applicable to the Gulf of Mexico (Stumpf *et al.* 2000) can estimate the chlorophyll without such a bias. Accurate chlorophyll estimation is essential to obtaining estimates of *K. brevis* concentration.

Satellite imagery can serve several purposes. While the goal is direct detection, imagery can provide a means of identifying blooms that should be sampled, and can also identify areas where *K. brevis* is not located, owing to the lack of chlorophyll. Imagery can also provide an estimate of the extent of a bloom in areas of low chlorophyll. Monitoring of blooms in 1999 and 2000 have shown that a comparison of satellite imagery with field programs offers a method for enhancing the monitoring for blooms.

CURRENT CAPABILITY OF IMAGERY FOR *K. BREVIS* BLOOMS

As few blooms occurred in the first year after the launch of SeaWiFS, the first actual application of the imagery began in 1999. In August 1999, dolphin and sea turtle strandings were reported along the Florida panhandle. Field sampling by the state of Florida revealed a *K. brevis* bloom at the coast, with cell concentrations of nearly 10^6 cells l^{-1}. Investigators had a critical concern about the extent of the bloom offshore. Satellite imagery indicated that surface chlorophyll concentrations more than a few kilometers offshore were too low (~0.3 µg/l) to support a significant

Table 2. Ocean color sensors.

sensor	mission	misc
CZCS (coastal zone color scanner)	1978-1986 (mostly 1979-1982)	experimental sensor, irregular coverage
OCTS (ocean color temperature sensor)	1996-1997	failed after 9 mos.
SeaWiFS (sea-viewing wide field-of-view sensor)	1997 - (five-year design)	1-2 day coverage, commercial
MODIS am (moderate resolution imaging spectrometer)	2000 - (not yet operational)	1-2 day coverage, government
MODIS pm	2001 launch	
GLI	2002 launch	

bloom. In addition, imagery from the preceding weeks gave no evidence of a surface bloom. This information allowed investigators to focus their efforts on the animals at the coast. With the purchase of SeaWiFS data through the NOAA CoastWatch program, real-time imagery became a routine part of the monitoring effort in September 1999. (Unlike other satellites, SeaWiFS data sets are the property of a commercial company, OrbImage, Inc., with usage subject to licensing restrictions. Fourteen-day-old imagery is available through NASA at no cost for research, but real-time imagery must be purchased for these applications.) Access to this imagery allowed us to combine the imagery with observations from the state monitoring programs to identify the position and status of blooms in the Gulf of Mexico through the 1999 and 2000 bloom seasons. However, the satellite imagery, with 1-km pixels, could not resolve blooms that persisted in the bayous of the small bays of the north Florida coast in late 1999. Valid data are problematic within 1 to 2 km of shore, a limitation of low resolution satellite imagery.

Spectral and optical methods may offer a potential for improved detection of *K brevis*, although primarily in deep and clearer water. Several researchers have been developing algorithms for detection of other types of algae (*e.g.,* coccolithophores by Brown and Yoder (1994); and Trichodesmium by Subramaniam and Carpenter (1994)), although more research is required for algal blooms in general (Cullen *et al.* 1997) and *K. brevis* specifically (Carder and Steward 1985). An alternative method, which shows promise in detecting *K. brevis* blooms, is a climatological analysis. In this analysis, the chlorophyll concentration field for a particular day is compared to the mean chlorophyll concentration field over the preceding 3 months. High anomalies, those > 1 μg l^{-1}, are classified as probably *K. brevis*. The technique has some assumptions that apply to the west Florida coast most subject to blooms. First, *K. brevis* blooms initiate in the late summer when blooms of other algae are less common (Tester and Steidinger 1997; Stumpf *et al.* 1998). Second, the water must have low levels of optically important constituents such as dissolved pigments. This eliminates areas such as the Big Bend region of Florida (which receives the tannin-rich Suwannee River), the tannin-rich 10,000 Islands region of South Florida (and Florida Bay) and the Louisiana coast (dominated by the Mississippi River plume). These areas, however, are not initiations zone and have extremely infrequent blooms (Tester and Steidinger 1997), so this is not a severe restriction.

This approach has been used twice to successfully identify a bloom. In January 2000, dolphin strandings were reported in the Florida Keys. An image was acquired, and an anomalous bloom with chlorophyll-a more than 5 μg l^{-1} above background was identified in an area northwest of the Keys. Subsequent shipboard sampling confirmed that a *K. brevis* bloom having cell concentrations up to 600,000 cells l^{-1} (equivalent to about 6 μg l^{-1} chlorophyll) was present in the area. Positioning of ships would have been problematic without the use of the satellite imagery. Subsequent monitoring by satellite, and confirmed by field observations, showed that this bloom passed south of the Keys and dispersed.

In October 2000, a major chlorophyll anomaly was identified off the southwest Florida coast (Plate 1*). Based on the imagery, the State of Florida was advised to sample this region, which had not yet had a report of a bloom or related impacts. Samples on October 19 confirmed a *K. brevis* bloom. Over the following week, the extensive nature of the bloom was corroborated by numerous reports of extensive

fish kills in the bloom area. The analysis of the imagery allowed state and local officials to anticipate the bloom and begin sampling at the coast before adverse effects were reported.

CONCLUSIONS

Ocean color observations from satellite offer a means of detecting and monitoring HABs, such as *K. brevis*, that dominate the phytoplankton biomass. The SeaWiFS sensor provides the first of several sensors suitable for this purpose. While work is being conducted on spectral and optical signatures, accurate determination of chlorophyll from satellite is a significant aid in HAB monitoring. Also, near-daily coverage is essential to assure sufficient usable imagery to document the blooms. As research progresses, additional information on optical characteristics of all phytoplankton will improve detection of HABs by discriminating those blooms that are not caused by *K. brevis* (*e.g.,* Brown and Yoder 1994; Subramaniam and Carpenter 1994). Using the current capabilities of SeaWiFS, we have begun routine monitoring of harmful algal blooms in the Gulf of Mexico. On the Florida coast, the satellite imagery has provided advanced detection of blooms, allowing the state and local officials to better direct resources for sampling. As we continue to improve and demonstrate the effectiveness of satellite imagery for detection, we anticipate that it will become a critical part of the monitoring and management strategy for harmful algal blooms in the Gulf of Mexico.

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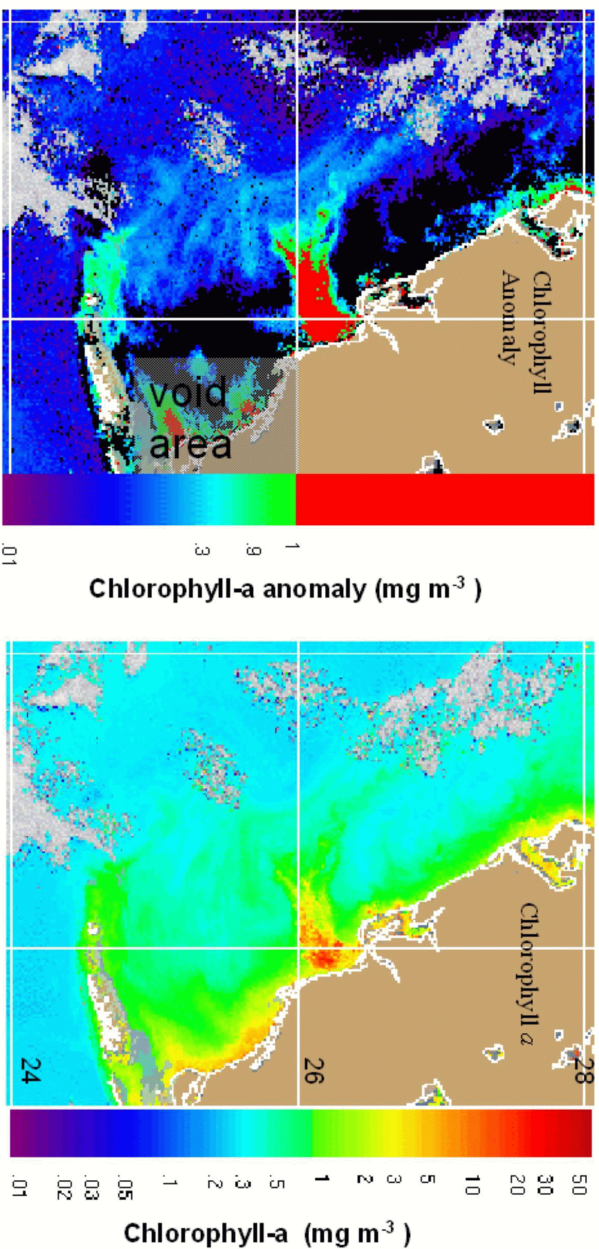
PLATE 1. Chlorophyll-a concentration and anomaly for southwest Florida coast in the Gulf of Mexico on October 18, 2000. Left image shows the October 18 chlorophyll-a anomaly of the image against the mean concentration for July-September, 2000. Areas in red are greater than 1 µg l⁻¹ indicating a possible *K. brevis* bloom. The shaded area noted as "Void" is subject to strong variations in apparent pigment owing to runoff from the coastal mangrove swamps and to instability in the optical algorithms in extremely shallow water. Right image shows the chlorophyll-a concentration. The *K. brevis* bloom was located around 82°W, just north of 26°N. Note that many areas, including the coastal bays where the chlorophyll concentration is high (>1 µg l⁻¹) do not show a meaningful anomaly. Stumpf et al. (2000) chlorophyll algorithm was applied. (Image data from Orbimage, Inc. processed by NOAA CoastWatch program.)